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Health Impact Assessment of Carbon-14 Emissions from Normal Operations of Uranium Fuel Cycle Facilities

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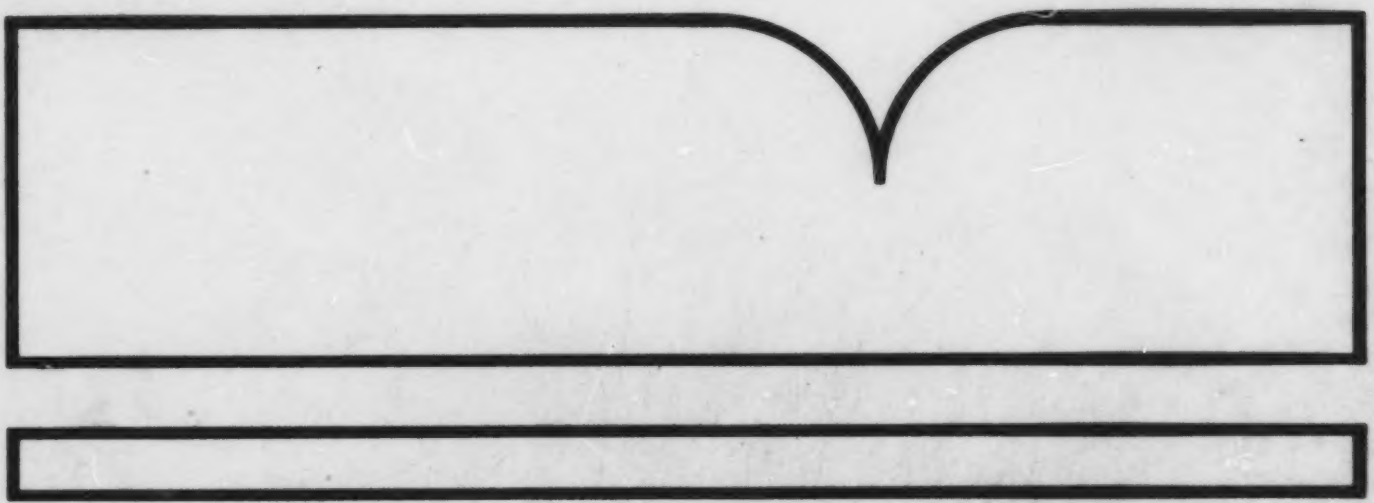

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16. ABSTRACT

A 1976 study by the U.S. Environmental Protection Agency estimated the public health impact of C-14 discharges from the light-water-cooled reactor (LWR) nuclear power industry. The study reported on here evaluates the environmental impact of C-14 discharges from LWR's and LWR fuel reprocessing facilities and updates the 1976 EPA estimates. The results of this study will be used to help deliberate the need for a national environmental standard for carbon-14 emissions from normal operations of uranium fuel cycle facilities.

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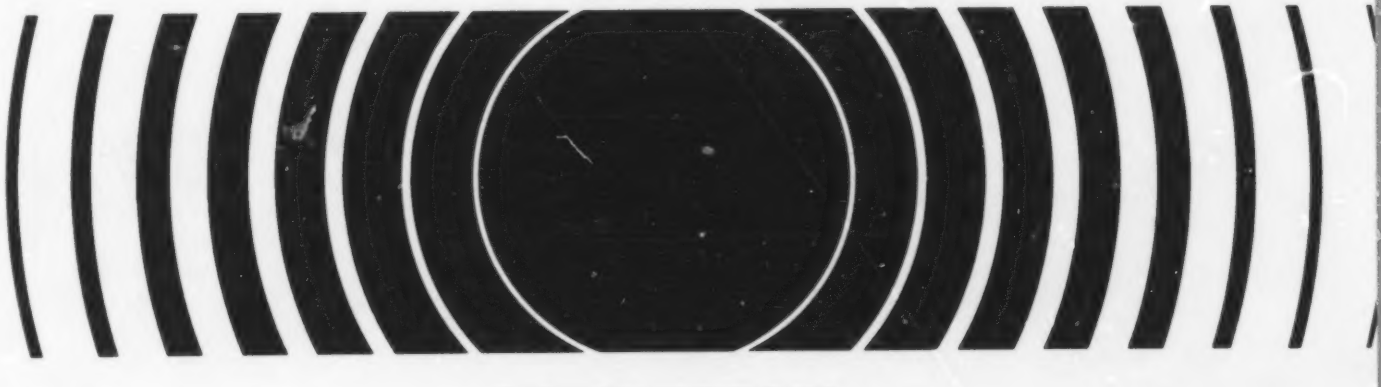

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HEALTH IMPACT ASSESSMENT OF CARBON-14 EMISSIONS FROM NORMAL OPERATIONS OF URANIUM FUEL CYCLE FACILITIES

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June 1979

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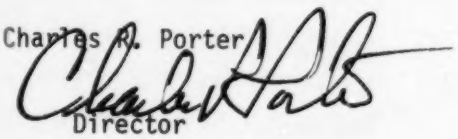
PREFACE

The Eastern Environmental Radiation Facility (EERF) helps solve problems defined by the Office of Radiation Programs. The Facility provides analytical capability for evaluating and assessing radiation sources through environmental studies and surveillance and analysis. The EERF provides special analytical support for Environmental Protection Agency Regional Offices and other federal government agencies as requested as well as technical assistance to the radiological health programs of state and local health departments.

Currently, the Environmental Protection Agency is evaluating the need for a national environmental standard for carbon-14 emissions from normal operations of uranium fuel cycle facilities. The study reported on here was performed to provide information on the health impact of carbon-14 and the methodology being used to estimate it. Readers of this report are encouraged to comment freely. Comments may be directed to the EERF directly or to the Office of Radiation Programs in Washington, DC.

Charles R. Porter



Director

Eastern Environmental Radiation Facility

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ABSTRACT

A 1976 study by the U.S. Environmental Protection Agency estimated the public health impact of C-14 discharges from the light-water-cooled reactor (LWR) nuclear power industry. The study reported on here evaluates the environmental impact of C-14 discharges from LWR's and LWR fuel reprocessing facilities and updates the 1976 EPA estimates. The results of this study will be used to help deliberate the need for a national environmental standard for carbon-14 emissions from normal operations of uranium fuel cycle facilities.

For a given release of C-14 to the atmosphere, 5 percent of the environmental dose commitment is delivered in the first 100 years after release, 50 percent in 5,000 years, and the balance tens to thousands of years after release. The additional fatal cancer risk to any single individual due to C-14 emissions from LWR facilities is estimated to be small. The fatal cancers and genetic effects committed to the world population due to C-14 emissions from LWR facilities is also small compared to the fatal cancers and genetic effects from environmental C-14 sources such as cosmic C-14 or C-14 released during nuclear weapons testing. The primary concern over uncontrolled discharges of C-14 from LWR facilities is the cumulative fatal cancers and genetic effects committed to the world population over long periods of time.

Carbon-14 risk coefficients indicating fatal cancers committed to the world population per curie of C-14 released to the atmosphere are estimated to be 4.1E-3 fatal cancers/Ci for 100 years after release and 7.8E-2 fatal cancers/Ci for infinite time. We assume that all C-14 produced by U. S. LWR facilities from 1976 to the year 2000 will be released to the atmosphere. From that release, we estimate that there will be 390 potential serious health effects committed to the world population during the next 100 years and 7500 over the next 40,000 years.

In addition to considering these findings on health impact, we recommend further study before deliberating the need for a national C-14 standard. Carbon-14 control technology, costs for LWR facilities, and the significance of summing very small doses to large numbers of people over long time periods to cumulate health effects should be addressed in additional studies.

INTRODUCTION

Carbon-14 discharges to the atmosphere are not likely to be a problem in the immediate future, but they can be in the more distant future. Carbon-14 has a long physical half-life, 5730 years. As such, C-14 released to the atmosphere becomes a permanent contaminant to the worldwide environment. Though, at present, there are only small environmental burdens of C-14 from nuclear power operations and only small estimated dose equivalents committed to any single individual, there is a clear concern about the cumulative risk from C-14 over long periods of time.

This report presents estimates of health impacts from uncontrolled discharges of C-14 from light-water-reactor (LWR) facilities and compares the health impacts from those C-14 discharges with discharges from other sources. To derive the individual lifetime and population dose commitments from discharges of C-14 to the atmosphere, we used a diffusion-type model of the global carbon cycle developed by G. G. Killough (Ki77a).

A previous EPA study (Fo76) also estimated health impacts from C-14 discharged to the atmosphere by the LWR industry. The study reported on here is different from the 1976 study in two main ways. First, whereas the 1976 study did not calculate the C-14 environmental dose commitment beyond 100 years after its release to the atmosphere, this study calculates the environmental dose commitment over the life of C-14 in the environment. Secondly, this study estimates C-14 health risk coefficients for somatic effects considering only the dose to the lean body mass, since the dose to adipose tissue is not effective in producing cancer. The 1976 study considered the dose to both the lean body mass and adipose tissue.

CARBON-14 SOURCE TERMS

Theoretical LWR Production Rates

Carbon-14 is produced in LWR's by the activation of the fuel, cladding, core structural materials, and coolant. Most carbon-14 in the fuel is produced by the (n,p) reaction with nitrogen-14 that is present as a fuel im-

purity; whereas, most carbon-14 in the coolant is produced by the (n, alpha) reaction with oxygen-17, which is only present in its natural abundance of 0.037%. Table 1 presents carbon-14 production rates calculated for LWR facilities by Davis (Da77a) using the ORIGEN code (Be73). Carbon-14 produced in the coolant and fuel is potentially available for release at the reactor and fuel reprocessing facility, respectively. We assume that carbon-14 produced in the cladding and core structural materials is unavailable for release to the air or water but contributes to the amount of carbon-14 disposed in radioactive waste.

C-14 Source Terms for LWR Facilities

The C-14 source terms for LWR facilities that we used in this evaluation are as follows:

LWR fuel cycle - 25 Ci/GWe-yr

LWR fuel reprocessing facility - 830 Ci/yr (18.4 Ci/GWe-yr)

PWR-5 Ci/yr (5 Ci/GWe-yr)

BWR-10 Ci/yr (10 Ci/GWe-yr)

Our LWR values are based on an analysis of measured values (Fo76) rather than theoretical estimates. The LWR values are supported by measured values reported by Riedel and Gesewsky (Ri77) and are similar to values used by the U. S. Nuclear Regulatory Commission (USNRC) in their regulatory guides NUREG-0016 (USNRC76a) and NUREG-0017 (USNRC76b). The NRC estimates (USNRC76a, USNRC76b) that the annual quantity of carbon-14 released from a reference boiling water reactor and pressurized water reactor is 9.5 Ci/yr and 8 Ci/yr, respectively. Their estimates are based on a simple activation calculation; however, the values are in reasonable agreement with the values selected for this analysis and with measurements to date of C-14 emissions at operating LWR's.

The C-14 source term for an LWR fuel reprocessing facility was calculated using Davis's (Da77) fuel production rates (see Table 1). To calculate average fuel production (18.4 Ci/GWe-yr), we assumed that the PWR accounts for approximately twice the produced power of the BWR. The reference LWR fuel reprocessing facility (Fo76) has a throughput capacity of 1500 metric tons heavy metal (MTHM) per year and an annual capacity to

Table 1. Carbon-14 production rates in LWR facilities (Da77)

Reactor type	Region of carbon-14 formation	Carbon-14 production rate Ci/(GWe-yr)
Boiling Water Reactor	Cladding and core structural materials *	43.3-60.4
	Fuel	17.6
	Coolant	4.7
Pressurized Water Reactor	Cladding and core structural materials *	30.5-41.6
	Fuel	18.8
	Coolant	5.0

*According to Davis (Da77), the calculated values for C-14 in the hardware are conservatively high, since they are based on the assumption that all core hardware - not just the cladding - is in an intense a flux field as is the cladding.

†These are median production rates based on a median nitrogen impurity of 25 ppm in the fuel. Lower or higher values depend on whether or not process precautions are taken to minimize nitrogen inclusion during fabrication.

process fuel which produced a nominal electric power output of 45 GWe-yr for a burnup of 33,000 MWt-days/MTHM at 33% thermal efficiency. Therefore, 830 curies of C-14 can be released annually from the LWR fuel reprocessing facility. For this evaluation, we assume that the C-14 released from the fuel reprocessing facility and the BWR is in the chemical form of carbon dioxide and in the non-CO_2 form (hydrocarbons) at the PWR (Fo76, Br77). The assumed chemical species of C-14 emissions at LWR's have been confirmed by a few measurements, but confirmation at the LWR fuel reprocessing facility awaits necessary laboratory data and/or actual field measurements.

Comparison of Theoretical and Measured C-14 Emission Rates

The carbon-14 production rates in Table 1 are based on theoretical calculations, and they are uncertain values. A few measurements of C-14 emission rates at LWR's have been compared to theoretical estimated emissions (Da77b, Fo76, Ri76). There is reasonable agreement between theoretical and measured C-14 gaseous emission rates at pressurized water reactors (PWR's); however, for boiling water reactors (BWR's), theoretical production rates are often lower than measured values by a factor of at least two. The theoretical values in Table 1 for the BWR appear low even without correcting for the large number of steam voids in the BWR reactor core coolant. By not correcting for the void fraction, the BWR core water mass is overestimated and the carbon-14 production by neutron (n, alpha) reaction with oxygen-17 will be overestimated.

The contribution by the neutron reaction with nitrogen-14 to measured C-14 emissions is unknown, since the nitrogen content of the coolant water at the time of the measurements was not reported. Measurements of the sources of C-14 production such as the nitrogen level in the coolant of LWR's are therefore needed. Another possible contribution to the higher measured BWR C-14 emission rates could be C-14 leaking from fuel tubes into the coolant water, since this source was not considered in the theoretically calculated C-14 gaseous emission rate.

Because of the uncertainties, we suggest that the following information be collected from several representative PWR's and especially BWR's:

1. measurements for each discharge stream of C-14 emissions (quantity discharged to the environment) concentration of C-14 and chemical form (carbon monoxide, carbon dioxide, hydrocarbons, etc.)

2. measurement where practicable of in-plant C-14 concentrations that input to the facility release of C-14 to the environment
3. measurements of contributing sources (e.g., nitrogen levels in the coolant, etc.) to the production of C-14 at the time of the C-14 emission measurements so that measured emissions can be compared to theoretical estimated emissions
4. collection of additional facility information pertinent to a theoretical calculation of the C-14 emission rate (e.g., mass of water in the BWR core accounting for any necessary correction for void fractions, effective neutron flux, etc.)
5. measurements of C-14 in ambient air surrounding the facility

In addition to measurements at LWR's, measurements of nitrogen in UO_2 fuel and C-14 liberated during fuel dissolution are needed to validate the C-14 LWR reprocessing plant source.

Davis (Da77a) has presented information supplied by five LWR-fuel manufacturers of nitride nitrogen and gaseous nitrogen in their fuels and fuel-rod void spaces. Based on Davis's (Da77a) analysis, it appears that production of C-14 in the fuel could be controlled by limiting the amount of nitrogen impurity during fuel fabrication. As for actual measurements of C-14 in spent LWR fuel, Davis (Da77a) refers to an experimental program (Ca76) that may confirm the theoretically calculated source terms.

Other Sources of C-14 Releases to the Atmosphere

There are other fuel cycle sources of C-14 releases to the atmosphere (e.g., thorium fuel cycle [high temperature gas-cooled reprocessing plant]) besides the LWR nuclear power industry, but we did not evaluate these. We estimate that the major nuclear industry releases of C-14 to the atmosphere to the year 2000 will be from the LWR fuel cycle. However, Killough (Ki78) evaluated the worldwide impact of C-14 from the world nuclear power industry and noted that the water cooled graphite-moderated reactor (GMR), which is being constructed in the Soviet Union, has a potential for releasing significant amounts of C-14 to the environment (800 ± 300 Ci/GWe-year, Da77a), even though its contribution to the world's total nuclear energy production is expected to be small. We hope that improvements will be made in the GMR design and control technology to minimize C-14 releases to the environment

once the production sources of C-14 are identified and an international awareness for the potential environmental impact of C-14 releases is achieved.

We did evaluate the potential health effects from cosmic C-14 and nuclear weapons testing C-14 to provide a perspective on C-14 discharges from the U. S. LWR nuclear power industry. Cosmic C-14 is produced at a rate of approximately 4×10^4 Ci/yr (Li76, Da77a), which sustains an environmental steady state inventory of about 3×10^8 Ci (Ki77a). Nuclear weapons testing can also produce C-14 by reactions of neutrons produced at the time of the explosion with nitrogen in the atmosphere. An aboveground burst will produce about twice as much C-14 as a surface burst since surface bursts "lose" about one-half of their neutrons to the ground (Du64). Table 2 presents nuclear testing C-14 source terms that we adopted from Killough (Ki78). To calculate the C-14 nuclear weapons testing source terms, Killough assumes that a 1-MT burst above the ground releases 2.07×10^4 Ci of C-14 to the atmosphere and that all atmospheric detonations are air bursts. The assumption, which Killough made and we adopted, that all detonations are aboveground was made to help offset the possible underestimation that results from unreported yields and unannounced events.

LWR Nuclear Power Growth Estimates

In this study, we used 1976 U.S. Energy Research and Development Administration (ERDA) (Han76) projections for the growth of nuclear power in the U. S. and the world (see Table 3). We calculated installed nuclear capacity for the 25-year period 1976 to 2000 using ERDA projections for the years 1975, 1980, 1990, and 2000 and estimated capacities for intermediate years by linear interpolation. We assumed that the nuclear capacity consists entirely of LWR's and that the PWR will account for approximately twice the installed capacity projected for the BWR. Foreign nuclear capacities include all countries except the U. S. and Eastern Bloc countries. World capacities are sums of U. S. and foreign nuclear capacities and, therefore, do not include Eastern Bloc countries.

Recent estimates (OECD77a, OECD77b, Ha79, Li79) that consider the

Table 2. Nuclear weapons testing C-14 source terms (Ki78)

Year	^{14}C Released (Ci)	Year	^{14}C Released (Ci)
1945	1.2×10^3	1960	2.1×10^3
1946	4.1×10^2	1961	1.5×10^6
1947	*	1962	2.2×10^6
1948	2.2×10^3	1963	*
1949	*	1964	4.1×10^2
1950	*	1965	4.1×10^2
1951	3.3×10^3	1966	1.4×10^4
1952	2.4×10^5	1967	6.4×10^4
1953	4.7×10^4	1968	1.2×10^5
1954	3.1×10^5	1969	6.2×10^4
1955	2.4×10^4	1970	1.1×10^5
1956	3.3×10^5	1971	1.6×10^4
1957	2.0×10^5	1972	2.7×10^3
1958	6.6×10^5	1973	5.2×10^4
1959	*	1974	1.2×10^4

Total (1945-1974) = 5.8×10^6 Ci

*Killough (Ki78) did not present an estimated C-14 yield from nuclear weapons tests in the atmosphere for these years.

Table 3. Installed Nuclear Capacity Projections
(GWe)

Year	United States		Foreign		World**	
	Low Case	High Case	Low Case*	High Case†	Low Case	High Case
1976	43	46	43	46	86	92
1977	47	52	57	62	104	114
1978	52	58	72	79	124	137
1979	56	65	86	95	142	160
1980	60	71	100	112	160	183
1981	73	90	126	155	199	245
1982	87	109	152	197	239	306
1983	100	128	178	240	278	368
1984	114	147	204	282	318	427
1985	127	166	230	325	357	491
1986	141	191	269	384	410	575
1987	154	216	308	443	462	659
1988	168	240	347	501	515	741
1989	181	265	386	560	567	825
1990	195	290	425	619	620	909
1991	214	323	486	705	700	1028
1992	232	356	546	791	778	1147
1993	251	389	606	877	857	1266
1994	269	422	667	963	936	1385
1995	288	455	728	1050	1016	1505
1996	306	488	788	1136	1094	1624
1997	324	521	848	1222	1172	1743
1998	343	554	909	1308	1252	1862
1999	362	587	969	1394	1331	1981
2000	380	620	1030	1480	1410	2100

*OECD/IEA Modified by USA evaluation
†OECD/IAEA
**These projections are for the free world since Eastern Bloc countries were not included

announced delays in constructing planned nuclear facilities present even lower nuclear power growth estimates than the low cases presented in Table 3. Therefore, we expect that the nuclear growth scenarios in Table 3 will not be exceeded and that actual growth rates will be lower than the estimated low case. The low case is used to represent a conservative estimate of the LWR nuclear power capacity to the year 2000. Where appropriate, the results of analyses using more recent nuclear growth scenarios are discussed in the text.

In order to estimate the total impact of C-14 from U. S. LWR's, we used the Oak Ridge Associated Universities (ORAU) estimate (Wh76) of potential power production: 2.25×10^4 GWe-yr. This estimate is based on an estimated 3×10^6 tons of uranium available to the U. S. at costs that can be afforded in an LWR and assumes a 1 GWe LWR with recycle that requires about 4000 tons of natural uranium during its 30 years of operating life.

Comparison of Cumulative Releases of C-14 to the Atmosphere

Figure 1 shows a comparison of cumulative releases of cosmic C-14, nuclear weapons testing C-14, and LWR nuclear industry C-14 releases to the atmosphere. We employed the following assumptions to generate the C-14 release rate comparison presented in Fig. 1.

1. The low case installed nuclear capability projections for the 25-year period 1976-2000 are those in Table 3. We believe the low case is a realistic conservative estimate of the future growth of the LWR industry to the year 2000.

2. The capacity factor (GWe produced electrical power/GWe installed electrical power) is 0.69.

3. The potential power production of U. S. LWR facilities is 2.25×10^4 GWe-yr (Wh76).

4. The annual discharge of C-14 from the LWR nuclear power industry is equal to the LWR produced electrical power in GWe-yr times 25 Ci/GWe-yr (see p. 2). Carbon-14 produced in the fuel and coolant is released to the atmosphere in the year that the electrical power is produced. (These assumptions result in a conservatively high C-14 release rate since the U. S. does not currently have commercial LWR fuel reprocessing, and fuel reprocessing constitutes 18.4 of the 25 Ci/GWe-yr.)

5. We used the yearly C-14 source terms in Table 2 to calculate the nuclear weapons testing C-14 cumulative releases for the period 1945-1974.

6. The cosmic C-14 production rate is $4x10^4$Ci/yr, which sustains a steady-state environmental inventory of about $3x10^8$ Ci ($4x10^4$Ci/yrx5730yr/0.693).

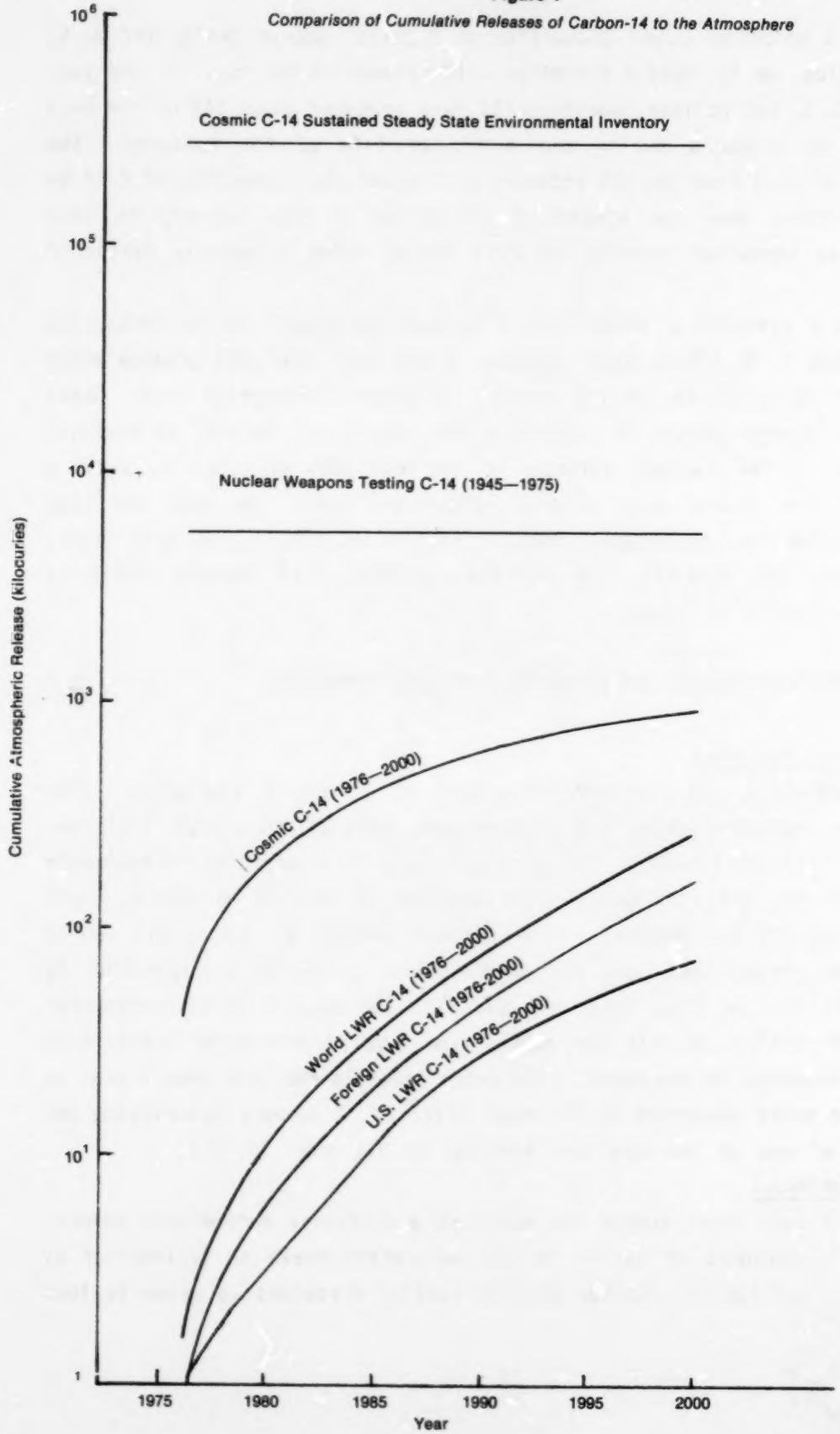
As illustrated by the curves in Fig. 1, we project that the cumulative environmental burden of C-14 to the end of the twentieth century from the LWR nuclear industry will be only a small fraction of the cumulative environmental burden of nuclear weapons testing C-14 or cosmic produced C-14. The cumulative atmospheric injection of C-14 from nuclear weapons testing was 5800 kCi for the years 1945 to 1974. The cosmic C-14 annual production rate of 40 kCi resulted in a cumulative atmospheric injection of 1,000 kCi after the 25-year period 1976 to 2000. Cumulative releases of C-14 from the LWR nuclear power industry after the 25-year period 1976 to 2000 are estimated to be 78.8 kCi for the U.S., 182 kCi for foreign facilities, and 261 kCi for the world. Using more recent energy production estimates (Ha79) for the U.S., about 49 kCi of C-14 will be released by U. S. LWR facilities between 1976 and the year 2000.

These release estimates for the U.S. industry are especially conservative since there are no operating commercial reprocessing plants in the United States. President Carter's nuclear energy policy included a decision to defer indefinitely the commercial reprocessing and recycling of plutonium in the U.S. Subsequently, the NRC issued a policy statement (USNRC77) terminating applications for reprocessing facility licenses. In light of the lack of current operating LWR fuel reprocessing facilities, the impact of C-14 releases from this portion of the uranium fuel cycle is currently zero. However, we have included an estimate of the health impact of C-14 emissions from LWR fuel reprocessing facilities to give a complete presentation of LWR facilities. Such information will be useful should the U.S. begin to reprocess fuel in the future.

The potential cumulative C-14 release to the atmosphere from the world LWR industry for the period 1976-2000 is about 25% of the cosmic C-14 produced during the same period, about 0.1% of the cosmic C-14 sustained steady state environmental inventory, and about 4% of the C-14 produced by nuclear weapons testing from 1945 to 1974. The U.S. LWR nuclear industry will release about 30% of the C-14 release from the world LWR industry.

Figure 1

Comparison of Cumulative Releases of Carbon-14 to the Atmosphere



Using a potential power production of 2.25×10^4 GWe-yr (Wh76) for U. S. LWR facilities, we estimate a potential C-14 release of 562 kCi. By the year 2000, the U. S. LWR nuclear industry will have produced about 14% of the C-14 that will be produced during the estimated life of the industry. The production of C-14 from the LWR industry will equal the production of C-14 by cosmic reactions when the electrical production of the industry is 1600 GWe-yr or an installed capacity of 2319 GWe-yr using a capacity factor of .69.

Figure 2 presents a comparison of production rates. We estimate that the world and U. S. LWR nuclear industry in the year 2000 will produce about 61% and 16% respectively, of the cosmic C-14 natural production rate. Using more recent energy production estimates for the U. S. (Ha79), we estimate that the U. S. LWR nuclear industry in the year 2000 will produce about 8 percent of the cosmic C-14 natural production rate. We used the same assumptions for the comparisons shown in Fig. 2 and Fig. 1. In both cases, we maximized the potential LWR nuclear industry C-14 release rates by assuming no control of C-14.

CARBON-14 DOSE EQUIVALENT AND ENVIRONMENTAL DOSE COMMITMENT

Environmental Transport

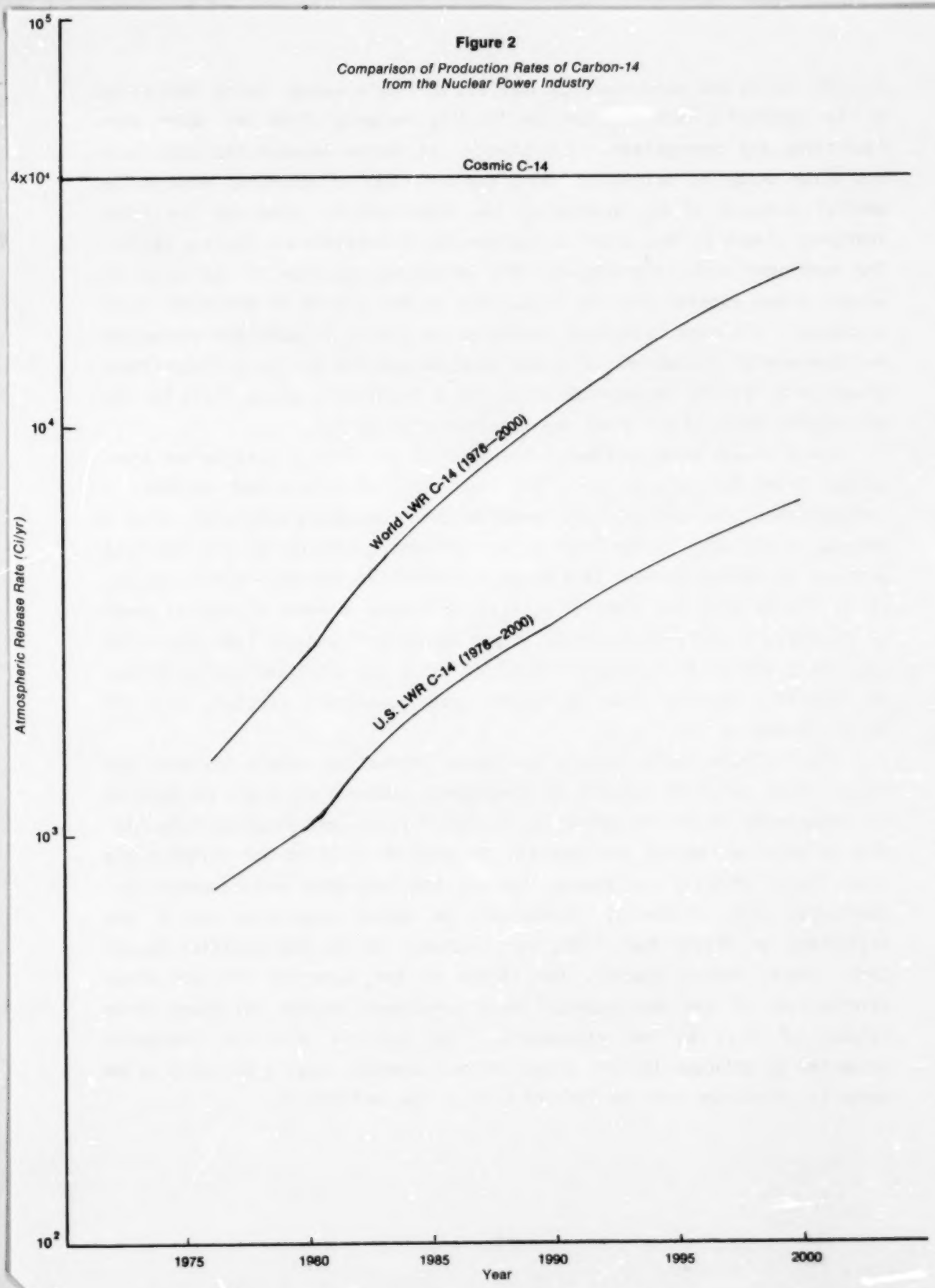
The worldwide environmental transport of carbon-14 atmospheric discharges was evaluated using a diffusion-type model of the carbon cycle developed by Killough (Ki77a). The Killough model is a world multi-reservoir model containing the atmosphere, slow turnover terrestrial biosphere, rapid turnover terrestrial biosphere, the surface waters of the ocean (mixed ocean), the thermocline, and the deep ocean. Based on a suggestion by Killough (Ki77b), an extra layer was added to the deep ocean as represented in ORNL-5269 (Ki77a) so that the equilibrium level from natural cosmic C-14 would be reproduced by the model. The extra layer is the only change that we made in the model described by Killough (Ki77a). A summary description and discussion of some of the important features of his model follows.

The Killough Model

The Killough model treats the ocean as a diffusive medium with respect to vertical transport of carbon in the subsurface ocean as implemented by Oeschger et al. (Oe75). Carbon dioxide readily dissolves in water to form

Figure 2

Comparison of Production Rates of Carbon-14 from the Nuclear Power Industry



carbonic acid, and this reaction involves so little energy change that it is easily reversible and CO_2 can be readily released from the ocean when conditions are appropriate. The transfer of carbon between the atmosphere and mixed ocean is calculated using the nonlinear relationship between the partial pressure of CO_2 exerted by the ocean surface water and the total inorganic carbon in this water as implemented by Bacastow and Keeling (Ba73). The nonlinear model accounts for the decreasing capacity of the ocean to absorb carbon dioxide from the atmosphere as the acidity of the ocean water increases. Killough calculates exchanges of carbon between the atmosphere and terrestrial biospheres using the Bacastow and Keeling (Ba73) logarithmic growth term for the terrestrial biota and a fractional growth limit for the terrestrial biota of 1.5 times the pre-industrial value.

The Killough model estimates the specific activity of C-14 in the atmosphere from the release of $^{14}CO_2$ into the atmosphere and includes a calculation of the carbon-14 environmental dose commitment (USEPA74), which is the sum of all doses to individuals over the entire time period that the C-14 persists in the environment in a state available for interaction with humans. It is assumed that the specific activity of carbon in human tissues is equal to the specific activity of carbon in the atmosphere, and the individual dose equivalent and the environmental dose commitment are calculated using carbon-14 specific activity dose equivalent rate conversion factors for the different body organs.

The Killough model uses a worldwide population growth scenario and assumes that increased amounts of atmospheric carbon dioxide are released to the atmosphere due to the combustion of fossil fuels containing no carbon-14. This assumption reduces the specific activity of C-14 in the carbon cycle (the "Suess Effect") and thereby reduces the long-term environmental dose commitment from carbon-14. Scenarios for world population growth and injections of fossil fuel $^{12}CO_2$ were included in the EPA modified Machta model (Ma74, Fo76); however, the choice of the scenarios did not allow calculations of the environmental dose commitment beyond 100 years after release of C-14 to the atmosphere. The improved plausible scenarios presented by Killough (Ki77a) allow the environmental dose commitment to be properly calculated over the life of C-14 in the environment.

Fossil Fuel Scenario

The injection of $^{12}CO_2$ into the atmosphere from the burning of fossil fuels is an important feature of the Killough model. Figure 3 is a plot of the production rate of fossil fuel $^{12}CO_2$ used in this analysis. For the years 1960 to 1974, production rates are computed by linear extrapolation of historical data tabulated by Keeling and Rotty (see ORNL-5269). For years beyond 1974, we used a logistic projection of the future release rate by solving the differential equation

$$\dot{P}(t) = RP(t) \left[1 - \left(\frac{P(t)}{P_\infty} \right)^n \right], \quad P(t_0) = P_0$$

where

$\dot{P}(t)$ = fossil fuel production rate (gC/yr) at time t,
R = adjustable parameter used to fit projections smoothly to historical data,
P(t) = cumulative production (gC) prior to time t,
P_∞ = total fossil fuel ultimately released (gC),
n = shape parameter, with increasing values of n decreasing the required time to exhaust the supply of fossil fuels, and
P_0 = cumulative production (gC) prior to a specified time t_0 (=1974).

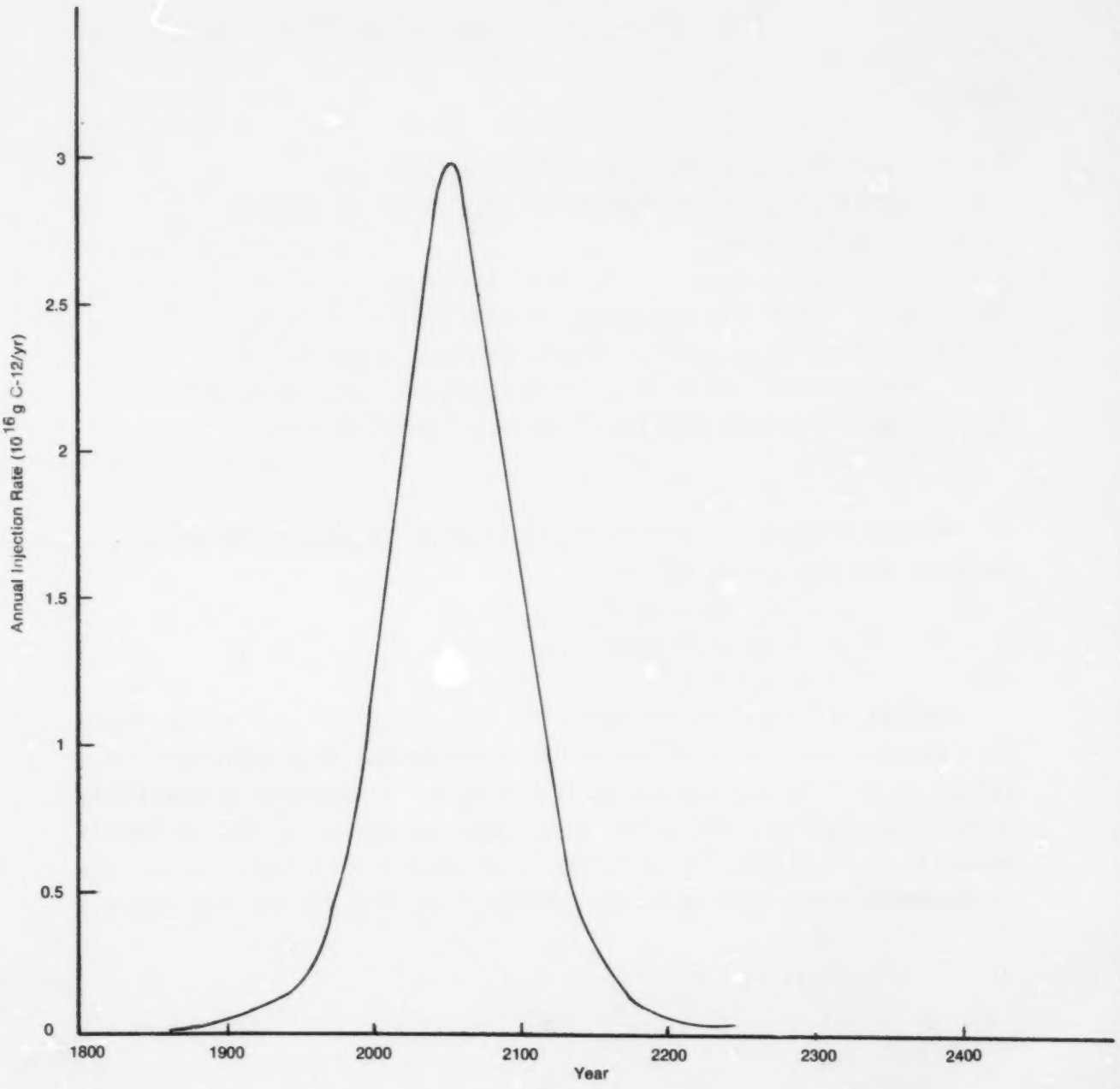
We used Killough's reference values to solve the above differential equation, and they are as follows:

$P_0 = 1.34 \times 10^{17}$
$P_\infty = 3.08 \times 10^{18}$
$n = 1$

However, Killough (Ki77a) found that the parameters used in the fossil fuel scenario had little effect on the environmental dose commitment for a release of C-14 to the atmosphere. For example, he found during sensitivity tests that doubling the total fossil-fuel projected to be ultimately released, P_∞ (3.08×10^{18} g to 6.16×10^{18} g), decreased by eight percent the environmental dose commitment for infinite time, but did not significantly

Figure 3

Annual Atmospheric Injection Rate of Fossil Fuel $^{12}CO_2$



affect environmental dose commitments calculated for time periods less than 100 years after release of carbon-14 to the atmosphere. Similarly, increasing the shape parameter n by 4 (0.5 to 2.0) did not affect the environmental dose commitment over infinite time, and the 100-year environmental dose commitment was only decreased by about 4%.

World Population Scenario

The environmental dose commitment calculation must consider world population growth over the next 40,000 years, since that is how long C-14 remains in the environment and available for interaction with man. In Killough's model (Ki77a), which we have adopted, the world population stabilizes at 12.2 billion from the year 2075 on. His reference world population growth scenario, shown in Fig. 4, is the United Nations' "medium" variant projection to the year 2075(UN74).

Infinite time environmental dose commitments calculated using Killough's model can be scaled up or down in accordance with alternative world population future growth scenarios. The United Nations' long-range projections (UN74) assume that "where any human behavior is concerned, no accurate prediction is possible" and "the more distant the future, the more hazardous is the venture." As for the employed asymptotic level of 12.2 billion for the world population, reports indicate that it may be high or low. According to Kahn (Ka76), who projects a decreasing population growth rate, the world population in 200 years "will total approximately 15 billion, give or take a factor or two."

Internal Dosimetry

An intermediate result of the Killough (Ki77a) worldwide C-14 environmental transport model is the specific activity of C-14 in the atmosphere. In order to convert this specific activity to a dose equivalent rate in man, we assumed that the specific activity of C-14 in the atmosphere and in man are the same. We derived carbon-14 specific activity dose equivalent rate conversion factors by the method outlined by Fowler (Fo76). Table 4 presents the resulting factors. Specific activity dose equivalent rate factors (DECF) were calculated using the following equations:

Figure 4

World Population Projection

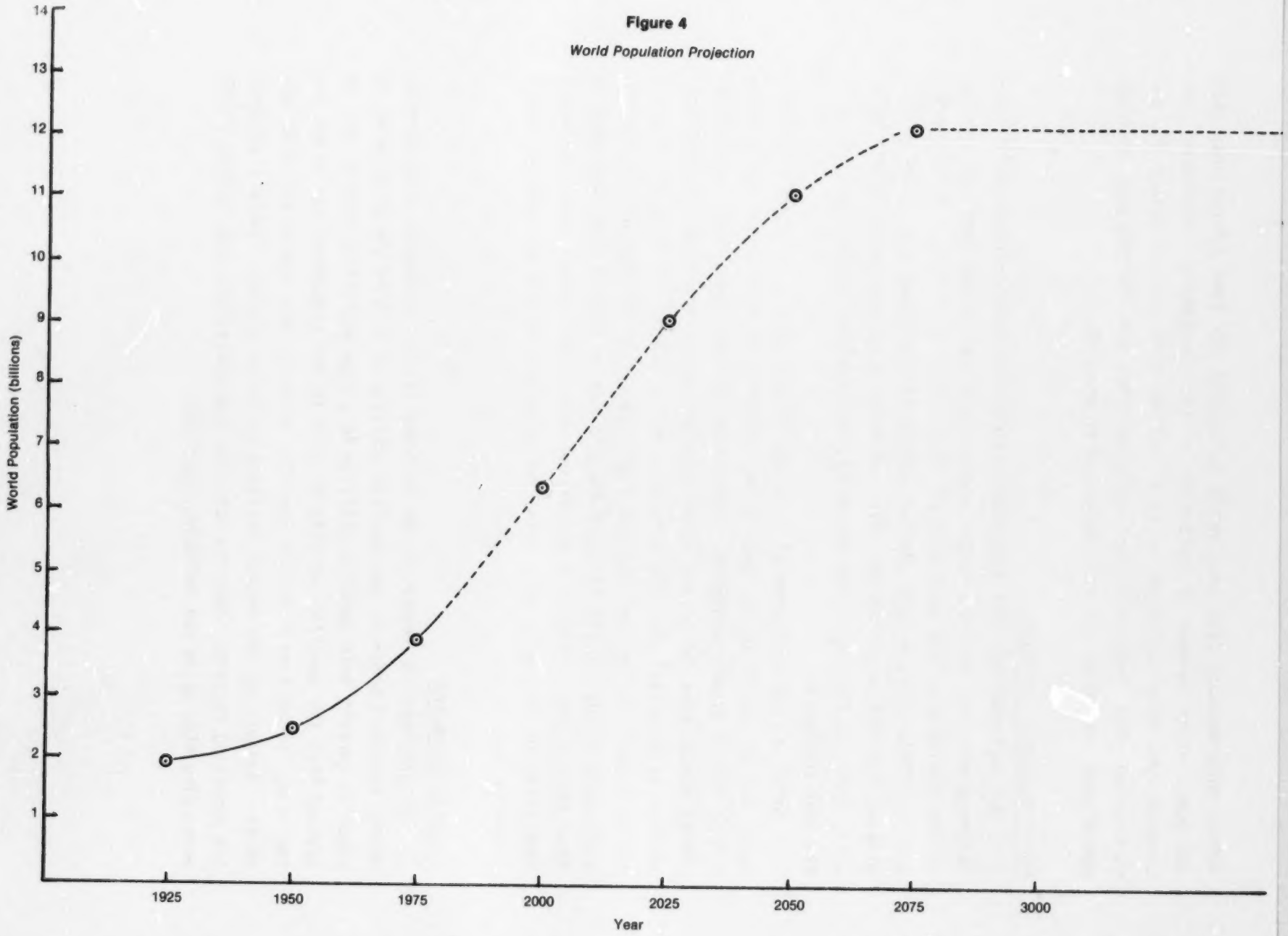


Table 4. Carbon-14 specific activity dose equivalent rate conversion factors

Organ	Dose equivalent rate conversion factor (DECF) (mrem/yr per pCi C-14/gm C)
Body Fat	0.68
Adipose Tissue (body fat plus yellow marrow)	0.59
Kidneys	0.12
Liver	0.13
Lungs	0.09
Cortical Bone	0.13
Trabecular Bone	0.12
Red Marrow	0.38
Yellow Marrow	0.58
Total Endosteal Cells	0.33*
Lower Large Intestine	0.11
Stomach	0.11
Skin	0.21
Testes	0.08
Ovaries	0.08
Female Breasts	0.13
Thyroid	0.10
Total Body	0.21
Total Body Less Adipose Tissue	0.11

*This conversion factor represents contributions from C-14 in cancellous bone, cortical bone, red marrow, and yellow marrow using data from Snyder (Sn74).

$$\dot{DECF} \text{ (mrem/yr per pCi C-14/gm C)} = 0.919\ M_C/M_T$$

and

$$\dot{DECF} \text{ (mrem/yr per pCi C-14/gm C)} = 0.365\ SM_C$$

where

M_C and M_T are the mass of carbon and mass of tissue respectively for the organ or tissue that the $\dot{DECF}$ is being calculated.

0.919 is the product [3.7 E + 10 dis/sec-Ci] x [1Ci/1E+12 pCi] x [0.0493 MeV/dis] x [1.6 E-6 ergs/MeV] x [1gm (tissue) rad/100 ergs] x [3.15 E+7 sec/yr] x [1 rem/rad] x [1.0 E+3 mrem/rem]

S = dose equivalent per unit accumulated activity (rem/μCi-day)

0.365 is the product [1 E-6 μCi/pCi] x [365 day/yr] x [1E+3 mrem/rem]

M_C and M_T are from ICRP Publication 23 (ICRP75). The "S" factor is the dose equivalent (rem) to a target organ per unit integrated activity (μCi-day) in the source organ, which can be equated to the dose equivalent rate (rem/day) per organ activity burden (μCi) for steady state conditions.

In order to calculate $\dot{DECF}$ factors in Table 4, we obtained carbon-14 "S" factors from Snyder (Sn74) for 22 source organs and 24 target organs, and M_C values are from ICRP Publication 23 (ICRP75). The dose equivalent rate to the total endosteal cells per unit C-14 specific activity in cancellous bone, cortical bone, red marrow, and yellow marrow was calculated using the "S" factor technique. The $\dot{DECF}$ values for the GI tract in Table 4 do not include the dose equivalent contributed by the migrating contents of the GI tract. The "S" factor method to calculate $\dot{DECF}$ factors for C-14 has also been employed by ERDA (USERDA75); and contributions from the migrating contents of the GI tract were included in the ERDA calculated values. Considering C-14 in tissue and in the migrating contents within the stomach and intestine,

DECF values of 0.14 and 0.16 mrem/yr per pCi C-14/gmC are inferred from ERDA (USERDA75) methodology.

The carbon content in the female ovaries and breasts was calculated using tissue composition and elemental carbon content data from ICRP Publication 23 (ICRP75). The female breasts (combined weight of 360 g) contained 46 grams of carbon, and the ovaries (combined weight of 11 g) contained 0.94 g of carbon. The specific activity dose equivalent rate conversion factor presented in Table 4 for the female breasts may be low, since the tissue composition in ICRP Publication 23 (ICRP75) is for pregnant females, who would have a higher water content in the breast than nonpregnant females. The C-14 DECF value for adipose tissue was also calculated using data from ICRP Publication 23 (ICRP75).

A considerable portion of the C-14 dose to the total body is to adipose tissue. However, since C-14 has not been shown to produce carcinoma in adipose tissues, a DECF factor was calculated for the total body less adipose tissue. And, since C-14 has a maximum beta energy of 0.156 MeV and a maximum range in water (or tissue) of about 0.012 inches (305 microns) (USHEW70), the C-14 deposited in adipose tissue is not expected to irradiate, to any significance, adjacent nonadipose tissue. Moreover, adipose tissue is located at selected depots rather than dispersed uniformly throughout tissue. To calculate the DECF factor for adipose tissue (see Table 4), we used a tissue mass (M_T) of 15,000 grams (13,500 grams body fat and 1500 grams yellow marrow) and a carbon mass (M_C) of 9600 grams (ICRP75).

Environmental Dose Commitment

As previously indicated, we used the Killough model (Ki77a) to estimate the environmental dose commitment (EDC) from discharges of C-14 to the atmosphere. The Killough model has a built-in total body specific activity dose equivalent rate conversion factor for C-14 of 2.08×10^8 rem/yr per Ci C-14/gC. Thus, EDC calculations with the Killough model will be for the total body. Dose equivalent rates and the environmental dose commitments to other organs are calculated by simple ratios using the organ specific DECF's in Table 4.

Figures 5 and 6 illustrate the buildup of the environmental dose commitment to the world population for a release of 1 Ci of C-14 in 1985. Approximately 5 percent of the environmental dose commitment to infinite time is delivered in the first 100 years after release; 22 percent within 1000 years; and 99 percent within 40,000 years after release.

Figure 5

Buildup of the Total Body Environmental Dose Commitment to the World Population for a Release of 1 Ci of C-14 to the Atmosphere in 1985

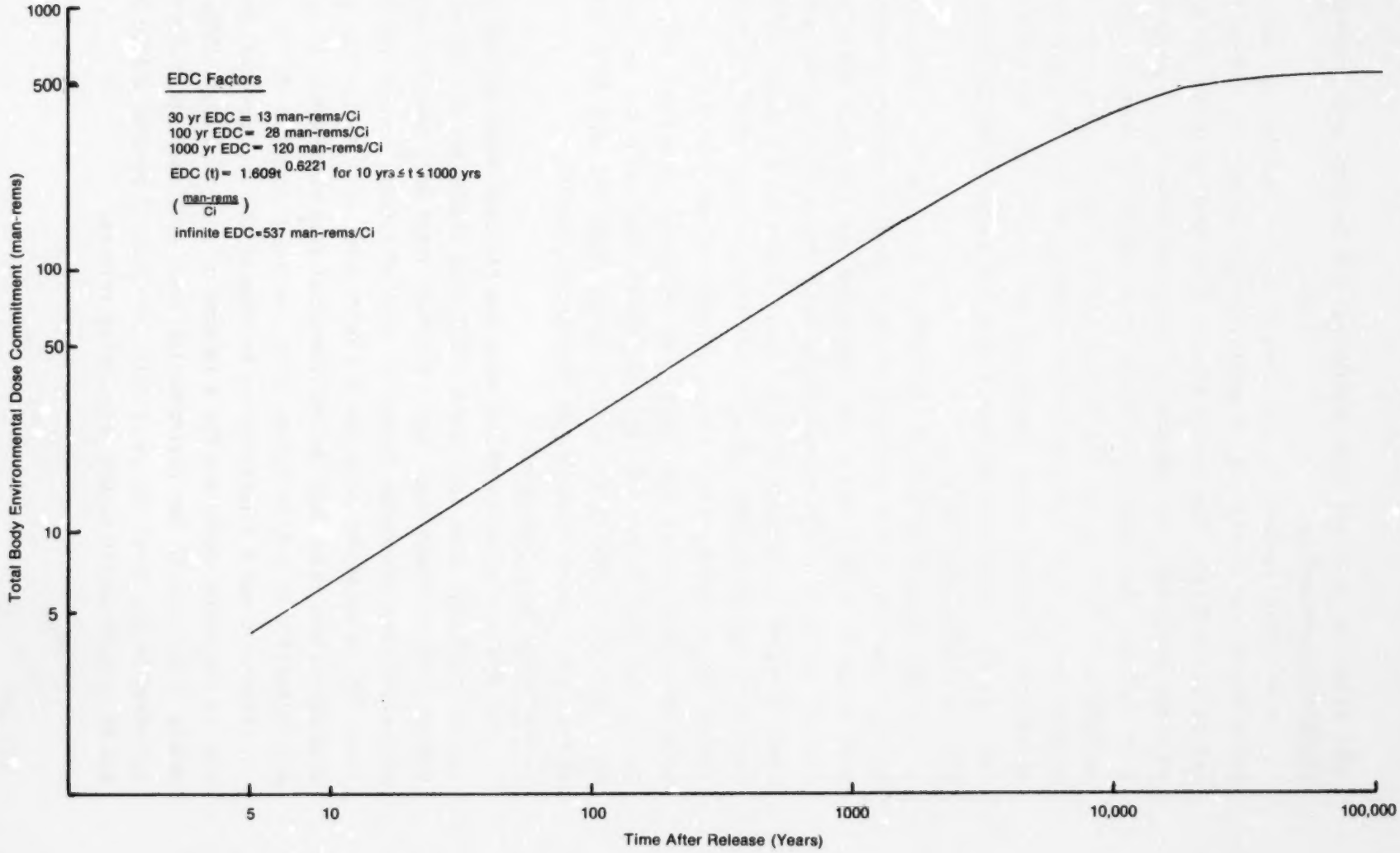
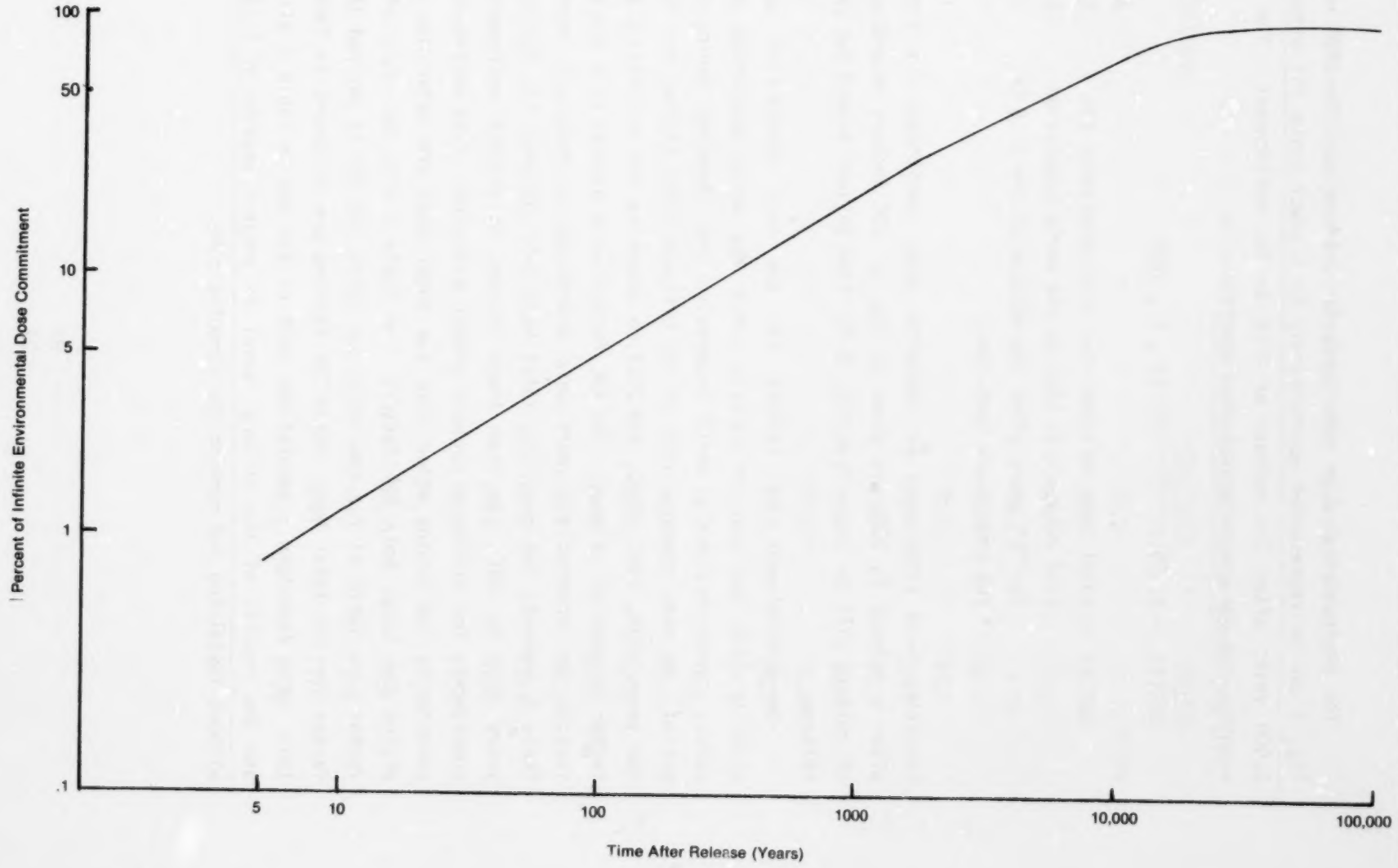


Figure 6

Buildup of the Total Body Environmental Dose Commitment to the World Population for a Release of 1 Ci of C-14 to the Atmosphere in 1985



The environmental dose commitment for C-14 releases in 1985 as shown in Fig. 5 can be represented approximately by a power curve fit between 10 and 1,000 years after the release of C-14 to the environment. The resulting equation for the environmental dose commitment is

$$EDC(t) = 1.609(t)^{0.6221} \text{ for } 10 \leq t \leq 1000$$

where

EDC(t) = total body environmental dose commitment for C-14 releases in 1985 to the world population for "t" years after the release of the C-14 to the atmosphere (man-rems).

Resulting C-14 total body environmental dose commitments for time periods after a release in 1985 are shown in Fig. 5. EDC factors regardless of year of release will be taken from Fig. 5 for time periods beyond 100 years after release.

One-hundred-year EDC factors for the next twenty-five years vary slightly with the year of release since the world population and stable carbon concentration in world reservoirs are changing during this time period. We made computer runs of the Killough model (Ki77a) for releases in the years 1975, 1985, 2000, and 2025 to determine the sensitivity of the EDC factor to year of release. The EDC factors were plotted on a graph, and EDC factors for intermediate years were determined by graphical interpolation. Table 5 presents the resulting total body C-14 100-year EDC factors for the years 1976 to 2000. We used these factors to project environmental dose commitments for different nuclear growth scenarios. C-14 environmental dose commitments for organs other than the total body are determined by multiplying the total body EDC factors from Table 5 with the ratio of the $\dot{D}\dot{E}\dot{C}F$ factor (see Table 4) for the organ for which the EDC is desired to the $\dot{D}\dot{E}\dot{C}F$ factor for the total body. Gonad EDC factors are presented in Table 5 using this ratio technique. Tabulations such as the one in Table 5 allow one to use the results of the Killough model to project impacts of C-14 releases without installing and running the computer code.

Table 5. Carbon-14 100-year environmental dose commitment factors

Year of Release	C-14 100-year EDC Factor (man-rems/Ci)	
	Total Body	Gonads
1976	25.5	9.71
1977	25.7	9.79
1978	25.9	9.87
1979	26.2	9.98
1980	26.4	10.1
1981	26.6	10.1
1982	26.8	10.2
1983	27.1	10.3
1984	27.3	10.4
1985	27.6	10.5
1986	27.8	10.6
1987	28.0	10.7
1988	28.2	10.7
1989	28.4	10.8
1990	28.6	10.9
1991	28.8	11.0
1992	29.0	11.0
1993	29.2	11.1
1994	29.4	11.2
1995	29.5	11.2
1996	29.7	11.3
1997	29.8	11.4
1998	30.0	11.4
1999	30.1	11.5
2000	30.3	11.6

Dose Equivalent and Dose Equivalent Rate

Computer runs were done to estimate the total body dose equivalent rate and lifetime dose equivalent to an average individual in the world population from C-14 releases to the atmosphere. Comparisons were made of dose equivalent rates due to releases of C-14 from the U. S. and world LWR nuclear power industry, cosmic C-14, and nuclear weapons testing C-14.

The C-14 source term from the U. S. LWR nuclear industry for the years 1976 to 2000 was developed using the installed nuclear capacity projections for the United States low case in Table 3. Produced power for each year was calculated using an assumed capacity factor of 69 percent for each year. Carbon-14 was assumed to be produced at a rate of 25 curies per GWe-yr of produced electrical energy, and it was further assumed that all C-14 produced was released (e.g., no C-14 control) in the year that it is produced. We used this conservative approach in order to scope the public health implications of C-14 discharges. The projected atmospheric release rates of C-14 are especially conservative considering the current absence of LWR fuel reprocessing.

A subroutine was developed to describe the time dependent C-14 injection rate from 1976 to the year 2000. This subroutine develops the function C14PRO(T), which is the C-14 source term used in the Killough model environmental dose commitment calculation. Appendix 1 lists the subroutine used to evaluate the USLWR nuclear power growth scenario.

Table 6 lists the data base used to calculate the release rate of C-14 from the U. S. LWR nuclear power industry (low case). Electrical energy production rates for the beginning of each year (LWRPRO) were calculated assuming that the production rate changes linearly with time during each year. The values of LWRPRO are chosen to give an energy production in each calendar year equal to those indicated as produced electrical energy in Table 6. The value of LWRPRO for 1976 was chosen so that the difference between the values for 1977 and 1976 would be the same as the difference between the values for 1978 and 1977. The mathematical development of LWRPRO is as follows:

assume, $(r_i + r_{i+1})/2 = P_i$ or $r_{i+1} = 2P_i - r_i$

and

$r_0 + r_2 = 2r_1$

where

r_i = electrical energy production rate at the beginning of year i (GWe-yr/yr) = LWRPRO(I)

P_i = mean electrical energy production (GWe) during year i (also has the same value as the electrical energy produced for year i(GWe-yr))

i = 0 for 1976, i = 1 for 1977, etc.

By mathematical manipulation, it can be shown that $r_0 = (3\ P_0 - P_1)/2$ and $r_i = 2P_{i-1} - r_{i-1}$.

Table 6 shows the resulting values of LWRPRO. The atmospheric injection rate of C-14 in curies per year is calculated to be 25 Ci per GWe-yr times LWRPRO (GWe). The injection rate in curies per year is multiplied by 0.2242 to convert it to grams per year. The C-14 annual atmospheric injection from the U. S. LWR nuclear power (low case) is presented in Table 6. A similar approach was used to calculate the release rate of C-14 from the world LWR nuclear power industry using the installed capacities for the low case as presented in Table 3. Appendix 2 lists the subroutine utilized to evaluate the world LWR nuclear power growth scenario. Appendices 3 and 4, respectively, list the subroutines used to estimate cosmic C-14 produced from 1976 to 2000 and nuclear weapons testing C-14 releases during the years 1945 to 1974.

Figure 7 and Tables 7, 8, and 9 present the results of the computer analysis of the various sources of C-14 discharges. Figure 7 shows the time dependence of the average worldwide individual total body dose equivalent rate due to C-14 releases for the years 1976 to 2000 from the U.S. LWR nuclear power industry. The peak total body dose equivalent rate is approximately 7.5×10^{-3} mrem/year. Using recent projections of the growth of the U.S. LWR nuclear power industry to the year 2000 (Ha79), the peak total body dose equivalent rate after 25 years of uncontrolled C-14 discharges is about 4.3×10^{-3} mrem/yr. Note that the dose equivalent rate decreases after the

Table 6. Release rate of carbon-14 from the US LWR nuclear power industry - low case

Year	Installed LWR Nuclear Capacity (GWe)	P_i Produced* Energy (GWe-yr)	LWRPRO(I) Energy Production Rate at Beginning of the Year (GWe)	C-14 Annual Atmospheric Injection (KCi/yr)†
1976	43	29.7	28.4	.742
1977	47	32.4	31.0	.811
1978	52	35.9	33.8	.897
1979	56	38.6	38.0	.966
1980	60	41.4	39.2	1.04
1981	73	50.4	43.6	1.26
1982	87	60.0	57.2	1.50
1983	100	69.0	62.8	1.72
1984	114	78.7	75.2	1.97
1985	127	87.6	82.2	2.19
1986	141	97.3	93.0	2.43
1987	154	106	102	2.66
1988	168	116	111	2.90
1989	181	125	121	3.12
1990	195	134	129	3.36
1991	214	148	140	3.69
1992	232	160	155	4.00
1993	251	173	165	4.33
1994	269	186	182	4.64
1995	288	199	190	4.97
1996	306	211	208	5.28
1997	324	224	214	5.59
1998	343	237	233	5.92
1999	363	250	241	6.24
2000	380	262	259	6.56
2001			265	

*Assumed capacity factor is 69%.
†Atmospheric emission C-14 source term is 25 Ci/GWe-yr.

Figure 7

Average Individual Total Body Dose Equivalent Due to Carbon-14 Releases for the Years 1976—2000 from the US LWR Nuclear Power Industry

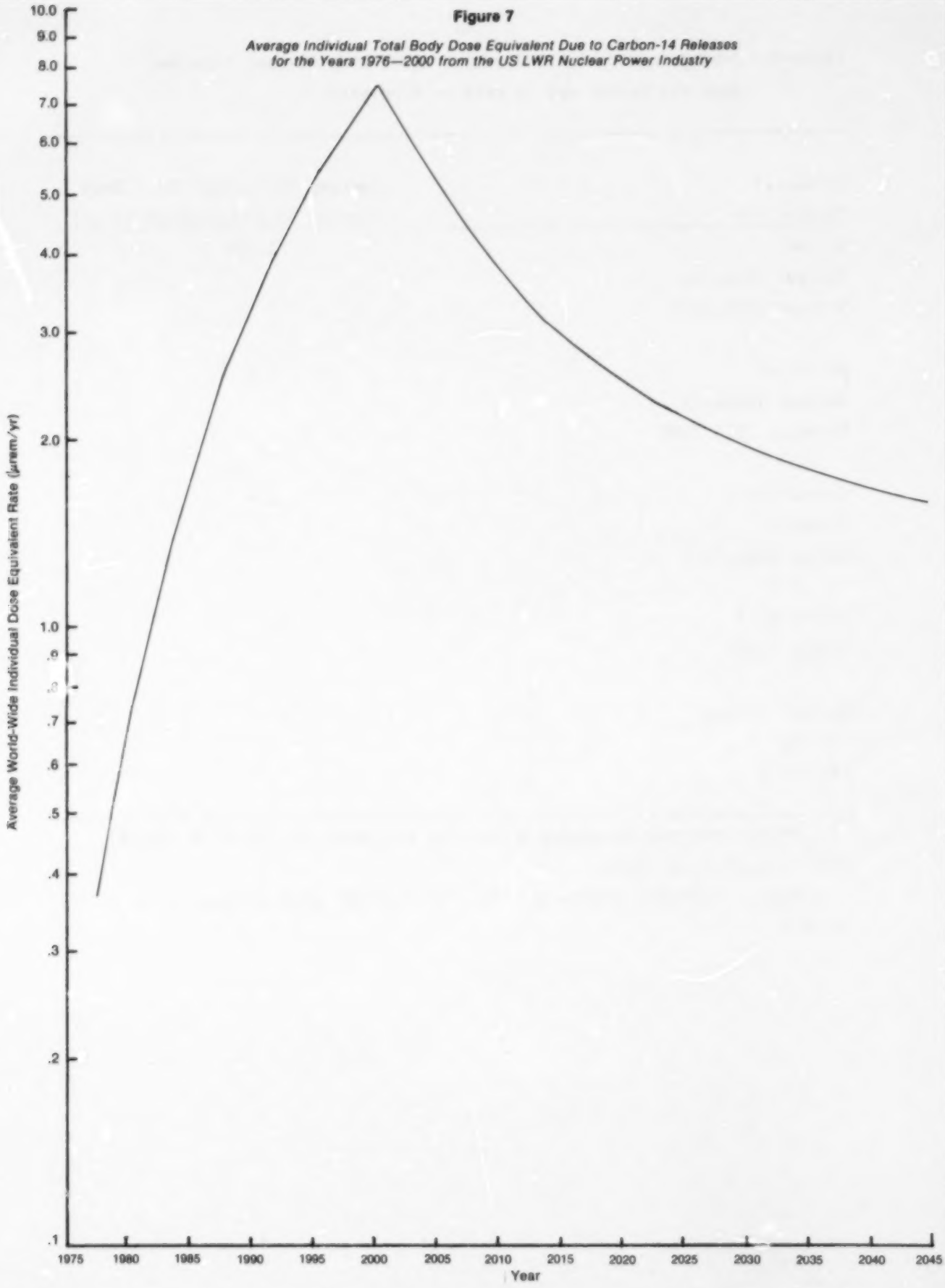


Table 7. Average world wide individual total body 70-year lifetime dose equivalent due to carbon-14 releases

Carbon-14 Source Term	Average Individual Total Body Lifetime Dose Equivalent (mrem)
US LWR Nuclear Industry Release 1976-2000	0.20*
World LWR Nuclear Industry Releases 1976-2000	0.67
Cosmic C-14 Produced During 1976-2000	2.8
Cosmic C-14 Steady State	91
Nuclear Weapons Testing 1945-1974	11

*Using more recent energy production estimates for the U. S. (Ha79), this value is 0.13 mrem.

Note.--Dose equivalents in this table are for an individual born in 1976.

Table 8. World population total body environmental dose commitment (man-rems) due to carbon-14 releases

Years after 1976	Carbon-14 Source Term: US LWR Nuclear Ind. Releases 1976-2000	World LWR Nuclear Ind. Releases 1976-2000	Cosmic C-14: Produced During 1976-2000	Cosmic C-14: Steady State	Nuclear Weapons Testing 1945-1974
50	1.2×10^{6} (7.3×10^{5})	3.8×10^{6}	1.5×10^{7}	4.2×10^{8}	9.1×10^{7}
100	2.0×10^{6} (1.2×10^{6})	6.6×10^{6}	2.6×10^{7}	1.2×10^{9}	1.4×10^{8}
500	6.2×10^{6} (3.8×10^{6})	2.1×10^{7}	7.9×10^{7}	7.9×10^{9}	4.6×10^{8}
1,000	9.4×10^{6} (5.9×10^{6})	3.1×10^{7}	1.2×10^{8}	1.6×10^{10}	7.0×10^{8}
10,000	3.1×10^{7} (2.0×10^{7})	1.0×10^{8}	4.0×10^{8}	1.6×10^{11}	2.3×10^{9}
20,000	3.9×10^{7} (2.4×10^{7})	1.3×10^{8}	5.0×10^{8}	3.2×10^{11}	2.9×10^{9}
40,000	4.2×10^{7} (2.6×10^{7})	1.4×10^{8}	5.3×10^{8}	6.4×10^{11}	3.1×10^{9}
infinite	4.2×10^{7} (2.6×10^{7})	1.4×10^{8}	5.4×10^{8}	∞	3.1×10^{9}

*Values in parentheses are those calculated using more recent energy production estimates for the U. S. (Ha79).

Table 9. World population total body environmental dose commitment per century after 1976 due to U. S. LWR nuclear industry carbon-14 releases 1976-2000

Years After 1976	Total Body Environmental Dose Commitment (man-rems)*
0-100	2.0×10^6 (1.2×10^6)
100-200	1.4×10^6 (9.4×10^5)
200-300	1.1×10^6 (6.6×10^5)
300-400	9.2×10^5 (5.8×10^5)
400-500	8.2×10^5 (5.1×10^5)
500-600	7.4×10^5 (4.6×10^5)
600-700	6.9×10^5 (4.3×10^5)
700-800	6.3×10^5 (3.9×10^5)
800-900	6.0×10^5 (3.7×10^5)
900-1,000	5.7×10^5 (3.6×10^5)
9,900-10,000	1.6×10^5 (9.8×10^4)
19,900-20,000	7.9×10^4 (4.9×10^4)
39,900-40,000	7.9×10^3 (4.9×10^3)

*Values in parentheses are those calculated using more recent energy production estimates for the U.S. (Ha79).

last year that C-14 was released to the atmosphere from the evaluated U.S. LWR nuclear industry growth scenarios. The dose equivalent rate due to C-14 releases from US LWR facilities will continue to increase after the year 2000 if the US LWR nuclear industry continues to release C-14 after this date. Based on the ORAU estimate (Wh76), the potential electrical energy production of US LWR's is 2.25×10^4 GWe-yr. From an analysis of the evaluated US LWR nuclear growth scenario, it is estimated that approximately 3.15×10^3 GWe-yr (1.96×10^3 GWe-yr for the 1979 projections (Ha79)) of electrical energy will be produced by the year 2000. Therefore, unless C-14 control systems are installed, C-14 releases from US LWR's will continue after the year 2000, and the average individual dose equivalent rate will increase above the values indicated in Fig. 7. The US LWR nuclear growth scenario evaluated in this analysis only extends to the year 2000 because of the large uncertainty associated with the estimated nuclear industry growth beyond the year 2000.

Cosmic C-14 is produced at a rate of approximately 4×10^4 Ci/yr, which sustains an environmental steady state inventory of about 3×10^8 Ci and a resulting specific activity of approximately 6×10^{-12} Ci/gC in the biosphere, from which the average worldwide individual receives a 1.3 mrem/yr total body radiation dose equivalent (Ki77a). Environmental dose commitments from the cosmic C-14 steady state level were calculated by multiplying the average dose equivalent rate of 1.3×10^{-3} rem/yr by the average world population size for the time period of interest and by the number of years of exposure. The lifetime average individual total body dose equivalent from the C-14 steady state level was simply calculated as 1.3 mrem/yr x 70 years = 91 mrems.

Table 7 shows the average worldwide individual, total body, 70-year lifetime dose equivalent due to C-14 releases. An individual born in 1976 is estimated to receive 102.67 mrem over his lifetime due to C-14 releases from the world LWR nuclear industry during the years 1976-2000, the cosmic C-14 steady state level, and C-14 releases from nuclear weapons testing during the years 1945 to 1974. Releases of C-14 from US LWR nuclear industry for the years 1976-2000 contribute 0.2 mrem of the estimated 102.67 mrem lifetime total body dose equivalent from C-14. Using more recent energy production estimates for the U.S. (Ha79), the average worldwide individual total body lifetime dose equivalent due to C-14 releases from the US LWR nuclear industry (1976 to 2000) is estimated as 0.13 mrem. The actual individual C-14

dose equivalent will be higher if releases of C-14 from fuel cycles other than LWR's are considered and if releases from the LWR nuclear industry are projected beyond the year 2000.

We assume the release of all the nuclear industry C-14 that is produced, thus the lack of fuel reprocessing or any installed C-14 control technology at LWR facilities would lower the estimated individual dose equivalent. Also, an individual living in the vicinity of a nuclear facility that releases large quantities of C-14 could receive a higher C-14 dose equivalent than the average worldwide individual. The extent of the increased dose equivalent to an individual residing in the vicinity of the nuclear facility will be determined largely by the nature of the facility release (daytime versus night), local meteorology (especially the frequency of daytime type A stability) (Ki76), and the dietary habits of the individual to whom the dose equivalent is being estimated.

Table 8 contains the world population total body environmental dose commitments due to C-14 releases from several sources of C-14 discharges to the environment. The environmental dose commitments for 50 and 100 years after 1976 were taken directly from the computer printout for computer runs using the Killough model. Except for the cosmic C-14 steady state source, environmental dose commitments for times greater than 100 years after 1976 were calculated by multiplying the total C-14 curie release for the release time period by the appropriate EDC factor. EDC factors regardless of year of release were taken from Fig. 5, so the resulting EDC is approximate, but accurate enough for the comparison purpose of this analysis.

The relative impacts of C-14 releases from LWR's, nuclear weapons testing, and cosmic C-14 are shown in Table 8. For example, the C-14 due to the world LWR nuclear industry releases for the 25-year period (1976-2000) is about 25% of the EDC due to the cosmic C-14 produced during this same quarter of a century, about 0.6% of the EDC due to the cosmic C-14 sustained steady state environmental inventory, and about 4.7% of the EDC produced by nuclear weapons testing C-14 from 1945 to 1974.

The EDC values in Table 9 for C-14 releases from the U. S. LWR nuclear industry are for different 100-year time periods after 1976. The impact is greatest in the first 100-year time period after 1976, and it decreases in the following centuries. However, a potential impact, though reduced, remains even at approximately 40,000 years after the release of the C-14 to the environment.

Estimated annual carbon-14 dose equivalent rates to individuals at the offsite location where maximum air concentrations occur at light-water-cooled reactors and fuel reprocessing plants are given in Table 10. Table 11 contains the assumptions we used to calculate the local dose equivalent rates. A specific activity model was used for the local maximum individual dose equivalent rate calculation. This method assumes that carbon-14 specific activity in the maximum individual is equal to the carbon-14 specific activity in the air at the maximum point of offsite concentration. Any food or fluids that the maximum individual ingests that are uncontaminated or at a lower C-14 specific activity than that at the point of maximum offsite concentration will lower C-14 dose equivalent rates below those in Table 10.

Table 12 shows the relationship of the C-14 dose equivalent rate to the total body dose equivalent rate from all radionuclides released from LWR's. The LWR impacts in Table 12 were estimated using the AIRDOS-II computer code (Mo77). Except for carbon-14, the airborne radionuclide emissions were taken from model BWR and PWR (with recirculating U-tube type steam generators) facilities as developed by the NRC and described in the final generic environmental statement on the use of recycled plutonium in mixed-oxide fuel in light-water-cooled reactors (USNRC76c). The annual release rates of C-14 were 9 Ci/yr and 5 Ci/yr for the BWR and PWR, respectively. The estimates represent a midwestern site in the United States. Food production and consumption assumptions for the maximum individual are for a rural setting. A 20-meter fixed stack height with no plume rise was employed. The regional population consisted of 2,486,049 people within an area having a radius of 80.4 kilometers. The maximum individual dose equivalent rate occurred 503 meters downwind. The dose equivalent rate from C-14 is a significant fraction of the total body dose equivalent rate received from all airborne radionuclides released from the model LWR facilities. The percentage of the maximum individual total body dose equivalent rate due to carbon-14 emissions is 22% for the BWR and 29% for the PWR. The percentage contribution by C-14 to the total body dose equivalent rate as obtained from data in Table 12 is appropriate only for the total body as the target organ. Percentage contributions for other target organs would have to be calculated separately. For example, carbon-14 contributes 16.4 percent to the lungs, 7.2 percent to the thyroid, and 18.5 percent to the ovaries of the maximum individual dose equivalent rate for the model PWR.

Table 10. Maximum individual carbon-14 total body dose equivalent rates for LWR facilities

Facility	Total Body Dose Equivalent Rate (mrem/yr)
LWR Fuel Reprocessing Facility	1.6
BWR	.86
PWR	.48

Table 11. Assumptions used for the calculation of the maximum individual carbon-14 total body dose equivalent rates for LWR facilities

Carbon-14 source terms	
LWR fuel reprocessing facility	830 Ci/yr
PWR	5 Ci/yr
BWR	9 Ci/yr
Maximum offsite atmospheric dispersion factor - "X/Q"	
LWR fuel reprocessing facility	5.0E-8 sec/m^3
PWR & BWR without stack	2.5E-6 sec/m^3
Concentration of carbon-14 in the troposphere	
0.174 gm C-12/m^3 (estimated for 1980)	
Specific activity dose equivalent rate conversion factor	
total body	0.21 mrem/yr per pCi C-14/gm C

Table 12. Total body dose equivalent rates for airborne emissions from BWR and PWR facilities

Facility	Maximum Individual (mrem/yr)	Average Individual (mrem/yr)	Regional Population (man-rem/yr)
BWR			
all radionuclides	1.8	3.5×10^{-3}	8.6
C-14 only	.41	5.6×10^{-4}	1.4
PWR			
all radionuclides	.78	2.3×10^{-3}	5.7
C-14 only	.23	3.1×10^{-4}	.78

HEALTH IMPACT ASSESSMENT OF C-14 DISCHARGES FROM THE LWR NUCLEAR POWER INDUSTRY

To project health impacts, we assumed a linear, nonthreshold relationship between the magnitude of the radiation dose received at environmental levels of exposure and ill health produced (USEPA75). This assumption is consistent with recommendations by the National Academy of Sciences - National Research Council's Advisory Committee on the Biological Effects of Ionizing Radiation (BEIR72). The general health effect risk factors that have been used previously by EPA in C-14 health impact assessments are 400 cancers (200 fatal and 200 nonfatal) per 10^6 man-rem to the total body and 200 serious genetic effects per 10^6 man-rem to the gonads (Fo76). Since a large percentage of the total body dose from C-14 is to adipose tissue and is not effective in producing cancer, we estimated new C-14 health risk coefficients that consider the dose to lean body mass. Table 13 presents resulting C-14 health risk coefficients as derived from an internal EPA memorandum (Ne78).

Since the average energy of a C-14 beta is 49 kev (median, 46 kev) and almost 100% absorbed in 50 μ , twice the diameter of a fat cell, no appreciable radiation is expected to escape the tissue from C-14 deposited in adipose tissue. If the C-14 beta radiation does not escape from adipose tissue, then only the risk to adipose tissue needs to be accounted for in the case of C-14 deposited in the tissue. The best evidence to date does not indicate any increased susceptibility to develop lipomas or liposarcomas following radiation exposure. Thus the risk to adipose tissue is considered to be zero (Ne78).

Lean body mass is approximated by the total body less adipose tissue target organ as described in the internal dosimetry section of this report. The leukemia risk from irradiation of the red bone marrow is considered separately, since it is two-thirds as great as the risk from all other tissues in the lean body mass exposed to carbon-14 (Ne78). Carbon-14 health effect risk coefficients presented in Table 13 per 10^6 man-rems to total body were calculated using the number of health effects per 10^6 man-rems to the target organ and the C-14 specific activity dose equivalent rate conversion factors in Table 4 of this report. For 10^6 man-rem exposure to the total body from C-14, the following health effects distribution was estimated: 58 leukemia deaths, 88 other cancer deaths, 105 nonfatal cancers, and 76 serious genetic effects.

Table 13. Carbon-14 health risk coefficients

Target Organ & Health Effect	Health Effect Risk Coefficients (Number per 10^6 man-rems to target organ)	(Number per 10^6 man-rems to total body)
Red bone marrow		
fatal leukemias	32	58
Lean body mass		
other fatal cancers	168	88
non-fatal cancers	200	105
Gonads		
serious genetic effects (all generations)	200	76

The health effects estimates are for C-14 beta irradiation only. No attempt was made to estimate the effect of $^{14}C \rightarrow {}^{14}N$ transmutation. The BEIR committee (BEIR72) noted that when there are many carbon-14 decays per nucleus that the radiation effects far outweigh the consequences of transmutation. The general conclusion was that it was justifiable to consider the main effect to come from the radiation emitted when the isotope disintegrates (BEIR72).

Estimates of the average worldwide fatal cancer risk and potential health effects committed to the world population from C-14 releases are in Table 14. The average worldwide individual fatal cancer risk was calculated using lifetime dose equivalents from Table 7 and the C-14 fatal cancer risk coefficient of 146 fatal cancers per 10^6 man-rems to the total body as presented in Table 13. Potential health effects include fatal cancers, nonfatal cancers, and serious genetic effects. The potential world population health effects for 100 years after the C-14 release was calculated using the 100-year environmental dose commitments in Table 8 and the C-14 health effect risk coefficients from Table 13.

Table 15 contains estimates of the local individual lifetime risks of fatal cancer and health effects committed to the regional population due to carbon-14 emissions from model BWR and PWR facilities. These health impacts were estimated using the total body dose equivalent rates from Table 12 and the carbon-14 health risk coefficients from Table 13. The lifetime fatal cancer risk to the highest exposed group of individuals is estimated to be 4.2E-6 for the BWR and 2.4E-6 for the PWR. The lifetime fatal cancer risk to the average individual in the region is estimated to be 5.7E-9 for the BWR and 3.2E-9 for the PWR. To make these individual risk assessments, we assumed that the exposure source would exist for at least 70 years. The individual lifetime fatal cancer risks in Table 15 will be in addition to the individual risk of cancer death from all causes of 0.15 (Bat79). The estimated cancer death risk of 0.15 is based on the American Cancer Society estimate that 25,000 out of 100,000 people will eventually develop cancer and that about 15,000 will eventually die of cancer.

Table 14. Average worldwide individual lifetime risk of fatal cancer and health effects committed to the world population from carbon-14 sources

Carbon-14 Source Term	Average Worldwide Individual Fatal Cancer Lifetime Risk (over 70 yrs.)	Potential World Population Health Effects (100 yrs. after C-14 Release)
US LWR Nuclear Industry Releases 1976-2000	2.9E-8 (1.9E-8)†	6.5E+2* (3.9E+2)†
World LWR Nuclear Industry Releases 1976-2000	9.8E-8	2.2E+3
Cosmic C-14 Produced During 1976-2000	4.1E-7	8.5E+3
Cosmic C-14 Steady State	1.3E-5	3.9E+5
Nuclear Weapons Testing 1945-1974	1.6E-6	4.6E+4

*The potential health effects committed to infinite time (essentially over the next 40,000 years) is estimated to be 1.4E+4(7.5E+3).†

†Values calculated using more recent energy production estimates for the U. S. (Ha79).

Table 15. Local individual lifetime risks of fatal cancer and health effects committed to the regional and world populations due to carbon-14 emissions from model BWR and PWR facilities

Individual Fatal Cancer Lifetime Risk (over 70 years)

	BWR	PWR
Maximum Individual	4.2E-6	2.4E-6
Average Individual	5.7E-9	3.2E-9

Regional Population Health Effects (one-year impact)

	BWR	PWR
Per year of plant operation	4.6E-4	2.6E-4

Worldwide Population Health Effects (100-year impact)

	BWR	PWR
Per year of plant operation	8.2E-2	4.6E-2

The number of health effects (fatal cancers, nonfatal cancers, and serious genetic effects) committed per year of site operation to the regional population is estimated to be 4.6E-4 for the BWR and 2.6E-4 for the PWR. The number of health effects committed to the world population from the annual C-14 release is estimated to be 8.2E-2 for the BWR and 4.6E-2 for the PWR. The health effects committed to the world population considered the impact over a 100-year period of time after release from one year's source term of carbon-14.

SUMMARY

The admonition of the National Environmental Policy Act of 1969 (NEPA69) that each generation should be a responsible "trustee of the environment for succeeding generations" is particularly germane to evaluating the health impact of C-14, which has a physical half-life of 5730 years. For a given release of C-14 to the atmosphere, 5 percent of the environmental dose commitment will be delivered in the first 100 years after release, 50 percent in 5,000 years, and the balance of the environmental dose commitment over a period extending tens of thousands of years after release.

The estimated health impact risk to any single individual from C-14 emissions from LWR facilities is small. The largest impact is the cumulative risk to population groups over long periods of time. Existing burdens of C-14 due to nuclear power operations are small, but the potential for future radiation effects may be large in the absence of a standard to limit the environmental burden of C-14. Assuming that all C-14 produced by U.S. LWR facilities during 1976-2000 is released to the atmosphere, approximately 390 potential serious health effects will be committed to the world population during the next 100 years. Seventy-five hundred potential health effects will be committed to infinite time (essentially over the next 40,000 years).

Carbon-14 risk coefficients can be expressed on a per curie basis to aid scientists in making evaluations of the impact of C-14 discharges to the atmosphere. Carbon-14 risk coefficients indicating fatal cancers committed to the world population per curie of C-14 released to the atmosphere are estimated to be 4.1E-3 fatal cancers/Ci for 100 years after release and 7.8E-2 fatal cancers/Ci for infinite time.

We recognize that the health impact due to C-14 emissions from LWR facilities is very small compared to that from background radiation or environmental C-14 sources such as cosmic C-14 or C-14 released during nuclear weapons testing. However, we share the view expressed by Killough and Till (Ki78) on comparisons of the health impact of C-14 emissions from LWR facilities and the potential health effects from natural and weapons-produced C-14: "These comparisons provide us with levels of exposure which are accepted as inevitable because they cannot be reduced" (Ki78). The comparisons provide perspective but should not be used to belittle the importance of controlling C-14 emissions if it could be done in a cost-effective manner. Carbon-14 control technology availability and costs for LWR facilities must be considered in deliberations on the need for a national C-14 standard.* This report outlines how the cumulative risk to the world population as well as individual risk can be used with C-14 control technology cost information to evaluate cost effective considerations.

Several issues besides cost effectiveness remain to be addressed. One is the significance of summing very small doses to large numbers of people over long time periods and cumulating health effects. Another is how potential health effects beyond 100 years in the future are to be addressed.

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*Two EPA contracted studies on this topic have been completed. Science Applications, Inc. assessed C-14 control technology and cost for the LWR fuel cycle (Br77). Nuclear Consulting Services, Inc., critically analyzed the SAI contract report (Ko79a) and provided an updated and more detailed analysis of C-14 control technology and costs for LWR facilities (Ko79b).

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APPENDIX 1

US LWR NUCLEAR INDUSTRY CARBON-14 RELEASES 1976-2000

C14PRO

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      FUNCTION C14PRO(T)

C
C     LWRPRO = PRODUCTION RATE OF ELECTRICAL ENERGY BY LWRS AT THE BEGINNING
C     OF EACH YEAR FOR 1976 THROUGH 2001.
C     THE PRODUCTION RATE IS ASSUMED TO CHANGE LINEARLY WITH TIME DURING
C     EACH YEAR.  VALUES OF LWRPRO ARE CHOSEN TO GIVE AN ENERGY PRODUCTION
C     IN EACH YEAR EQUAL TO THAT IN TABLE-3 (US LWR LOW CASE).
C     THE VALUE OF LWRPRO FOR 1976 WAS CHOSEN SO THAT THE DIFFERENCE BETWEEN
C     THE VALUES FOR 1977 AND 1976 WOULD BE THE SAME AS THE DIFFERENCE
C     BETWEEN THE VALUES FOR 1978 AND 1977.  THE ATMOSPHERIC INJECTION
C     RATE OF CARBON-14 IS TAKEN TO BE XCI*LWRPRO (CI/YR).  THE INJECTION
C     RATE IN CI/YR IS MULTIPLIED BY 0.2242 TO CONVERT IT TO GRAMS/YR.
C
      REAL LWRPRO(26)/ 28.35,  31.05,  33.75,  38.05,  39.15,  43.65,  57.15,
     *                 62.85,  75.15,  82.25,  92.95, 101.65, 110.95, 120.85,
     *                128.95, 140.05, 155.35, 164.85, 181.55, 189.65, 207.75,
     *                214.45, 232.75, 240.65, 258.95, 265.45/
      DATA XCI/25.0/
      CI4PRO=0.0
      IF (T.LT. 1976..OR.T.GE.2001.) RETURN
      I=T-1975.
      F=AMOD(T,1.0)
      C14PRO=XCI*((1.0-F)*LWRPRO(I)+F*LWRPRO(I+1))*0.2242
      RETURN
      END
```

APPENDIX 2

WORLD LWR NUCLEAR INDUSTRY CARBON-14 RELEASES 1976-2000

```
      FUNCTION C14PRO(T)
C
C     LWRPRO = PRODUCTION RATE OF ELECTRICAL ENERGY BY LWRS AT THE BEGINNING
C     OF EACH YEAR FOR 1976 THROUGH 2001.
C     THE PRODUCTION RATE IS ASSUMED TO CHANGE LINEARLY WITH TIME DURING
C     EACH YEAR.  VALUES OF LWRPRO ARE CHOSEN TO GIVE AN ENERGY PRODUCTION
C     IN EACH YEAR EQUAL TO THAT IN TABLE-3 (WORLD LWR LOW CASE).
C     THE VALUE OF LWRPRO FOR 1976 WAS CHOSEN SO THAT THE DIFFERENCE
C     BETWEEN THE VALUES FOR 1977 AND 1976 WOULD BE THE SAME AS THE
C     DIFFERENCE BETWEEN THE VALUES FOR 1978 AND 1977.  THE ATMOSPHERIC
C     INJECTION RATE OF CARBON-14 IS TAKEN TO BE XCI*LWRPRO (CI/YR).
C     THE INJECTION RATE IN CI/YR IS MULTIPLIED BY 0.2242 TO CONVERT
C     IT TO GRAMS/YR.
C
      REAL LWRPRO(26)/    56.235,  66.585,  76.935,  94.185, 101.775, 119.025,
     *                   155.575, 174.225, 209.375, 229.425, 263.175, 302.625,
     *                   334.975, 375.825, 406.575, 449.025, 516.975, 556.625,
     *                   625.975, 665.625, 736.375, 773.425, 843.975, 883.825,
     *                   952.975, 992.825/

      DATA XCI/25.0/
      C14PRO=0.0
      IF(T.LT.1976..OR.T.GE.2001.) RETURN
      I=T-1975.
      F=AMOD(T,1.0)
      C14PRO=XCI*((1.0-F)*LWRPRO(I)+F*LWRPRO(I+1))*0.2242
```

APPENDIX 3

COSMIC CARBON-14 PRODUCED DURING 1976-2000

C14PRO

```
      FUNCTION C14PRO(T)
C
C     COMPUTES RATE (GRAMS PER YEAR) AT WHICH C-14 IS BEING INJECTED
C     INTO THE ATMOSPHERE.  THIS VERSION OF THE SUBPROGRAM
C     ESTIMATES THE COSMIC PRODUCTION FOR THE YEARS 1976-
C     2000 AS 40000 CI/YR (=8968 GM/YR).
      C14PRO=0.0
      IF(T.GE.1976. .AND. T.LT.2001.) C14PRO=8968.0
      RETURN
      END
```

APPENDIX 4

WEAPONS TESTING CARBON-14 RELEASES 1945-1974

```
      FUNCTION C14PRO(T)
C
C     COMPUTES RATE (GRAMS PER YEAR) AT WHICH C-14 IS BEING INJECTED
C     INTO THE ATMOSPHERE.  THIS VERSION OF THE SUBPROGRAM
C     ESTIMATES THE NUCLEAR WEAPONS TESTING PRODUCTION DURING THE YEARS
C     1945 - 1974.  DATA IN CI/YR FROM KILLOUGH (Ki78) AS SHOWN IN
C     TABLE-2.
      REAL BOMB(30) /1.2E3, 4.1E2, 0.0,   2.2E3, 0.0,   0.0,   3.3E3, 2.4E5,
     *              4.7E4, 3.1E5, 2.4E4, 3.3E5, 2.0E5, 6.6E5, 0.0,   2.1E3,
     *              1.5E6, 2.2E6, 0.0,   4.1E2, 4.1E2, 1.4E4, 6.4E4, 1.2E5,
     *              6.2E4, 1.1E5, 1.6E4, 2.7E3, 5.2E4, 1.2E4/
      C14PRO=0.0
      IF(T.LT.1945..OR.T.GE.1975.) RETURN
      I=T-1944.
      C14PRO=BOMB(I)*.2242
      RETURN
      END
```